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Urban Flood Vulnerability and Risk Mapping using Multi-Criteria Analysis in Mzuzu City, Malawi

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Abstract
This paper presents the results of the assessment of flood vulnerability of Mzuzu City using Multi-criteria analysis and GIS. Using a Weighted Overlay approach, physiogeographic variables that influence floods such as drainage density, elevation, slope, landuse/landcover and soil type, were integrated and ranked based on their importance. From this assessment, urban flood risk map for the City was derived. The results show that 12% of the total area (112 sq. km.) of Mzuzu City has very high risk of flooding, 29% has high risk, 41% has low risk and 18% has very low risk of flooding. Both very high- and high-risk zones are located in the low-lying and flat central part of the City. The Northern and Easterly parts are low risk zones while the southern part are very low risk areas. LU/LC changes have exacerbated the degree of vulnerability of the city. High population growth has led to changes in LU/LC patterns. Built-up Area/Settlement and Bareground/Paved have increased while Dense Vegetation and Dambo Land have reduced considerably. The adoption and use of the generated flood risk vulnerability map by authorities will help to quickly assess potential hazardous areas and the impact of flood hazard. It can further guide in the commencement of appropriate measures to reduce its impacts in pre-disaster and post-disaster situations.
Keywords: Analytical Hierarchical Process (AHP), Geographic Information System (GIS), Landsat Images, Multi-criteria analysis, Reclassification, Weighted Overlay, Urban texture typology.

1.0 Introduction

The nature of flooding events experienced in Mzuzu City is becoming dynamic in time and space. Due to urbanization and the subsequent increase in population, urban texture keeps on changing. Land meant for agricultural activities, natural vegetation and wetlands have been converted into built-up environments (Stewart and Oke, 2012). With the sporadic infrastructural developments taking place, Mzuzu is characterized by a highly distorted urban texture typology of built types as well as land cover types. The most devastating flood occurred in 2016 where 15 settlements were affected. During these floods 19,000 people were displaced and 7 people lost their lives (Kita, 2017). The most affected areas were Masasa, Chibanja, Ching'ambo and Chibavi. These are informal settlements characterized by poor service provision, congestion and poor sanitation. Such dwellings are developed in wetlands and seasonal dambo lands with poor drainage. These conditions, coupled with human-induced climate change, render Mzuzu City more vulnerable to flood risk necessitating the acquisition of accurate spatial and temporal information regarding possible hazards and flood risks.

1.1. Conceptual Framework of Urban Flood Risk

The analysis and assessment of flood risk in an urban setting requires the development of a theoretical framework that captures all the various components contributing to the generation of urban flood risk (Muller, 2013). Flood risk consists of hazard and vulnerability (Merz et al., 2010). Hazard refers to a threatening event, or probability of occurrence of a potentially damaging phenomena within a given time and area. The damage that ensues when a hazardous event occurs depends on the elements at risk which include population, building structures, economic activities, public services and infrastructure. Therefore, when assessing the risk of damage due to natural hazards in general, at least two factors need to be taken into account. First is the probability and consequences. Second are the elements and their economic values (Estoque, 2010).

The second component of risk assessment which aims to quantify the damage potential (Merz et al., 2010), especially in complex and heterogeneous urban setups where elements at risk are affected unequally resulting into different types of damages, is vulnerability (Satterthwaite, et al., 2007). Muller (2013) defines vulnerability as the social and physical conditions that make parts of an urban system susceptible to experiencing damage from a flood event. People are the main actors in the generation of risk and its reduction. It is imperative therefore to identify the population characteristics as well as its associated urban infrastructure that lead to different levels of risk within an area. The better the knowledge about the amount and the capacities of people and values potentially affected, the more appropriate measures can be planned (Muller, 2013). Equation 1 considers risk as a product of three components i.e. hazard, elements at risk, and vulnerability (Muller, 2013).

$$\textbf{Risk} = \text{Hazard} \times \text{Elements at risk} \times \text{Vulnerability} \quad \text{…………..… (Equation 1)}$$

1.2. Multi-criteria Evaluation (MCE)

MCE is a decision theory of applying a decision rule to a set of alternatives whereas a ‘decision rule’ is a procedure by which criteria are combined to arrive at a particular evaluation, and by which evaluations are compared and acted upon (Eastman, 2001). A decision is a choice between alternatives while a criterion is a basis on which a decision is made. Two types of criteria may be identified thus factors and constraints (Estoque, 2010). The former is generally considered to be continuous in nature, and indicate the relative suitability of certain areas. The latter are Boolean in nature and serve to exclude certain areas from consideration. Using any Boolean method, factors and constraints can be combined in the MCE scheme (Estoque, 2010). MCE process aims at aggregating a set of criteria so as to realize one composite basis for decision making in line with a specific objective (Ouma and Ryutaro, 2014: Eastman, 2001).

1.3. Spatial Information and MCE for Flood Risk Mapping

Almost 80% of the data used by decision makers is geography-related (Bhadra et al., 2011). For one to ably prepare for a disaster, sufficient geographic information on hazards and vulnerable areas is a requirement. As such GIS, through its overlay process, is better placed to providing better information about situations that require decision making (Bhadra et al., 2011). The application of GIS in flood hazard analysis has many advantages. GIS does not only provide a visualization of the flooding, but it also provides room for probable estimation of damage caused by floods (Eastman, 2001). As opposed to the traditional mapping, GIS allows for multi-dimensional analyses of natural hazards. It allows comparisons across spatial units and across different spatial themes. GIS allows for performance of logical and/or numerical operations through merging of several spatial databases. GIS is time and cost-effective technology for extraction and provision of information of flood inundation magnitudes in hilly areas where conventional surveys is difficult to conduct (Ouma and Ryutaro, 2014).

2. Materials and Methods

2.1. Study Area

Mzuzu City is located in the northern Malawi between the boarders of Mzimba and Nkhatabay districts. It is the largest urban centre in the northern Malawi covering an area of 112km^2 and third largest urban centre in Malawi, after Blantyre and Lilongwe. Its population is 221,272, 60% of which lives in informal settlements (Malawi National Statistical Office, 2019). It is confined within the natural gap of Viphya Mountains where the terrain is generally flat with some gentle slopes dissected by some ridges and gullies. Main rivers that drain Mzuzu are Lunyangwa and Ching’ambo rivers which run from east to west and from north to south respectively. There are several streams that drain the southern part of the city and these include Katoto, Kavuzi and Kajiliwe (Leenaars, Dijkshoorn, Huting, & Kempen, 2016).

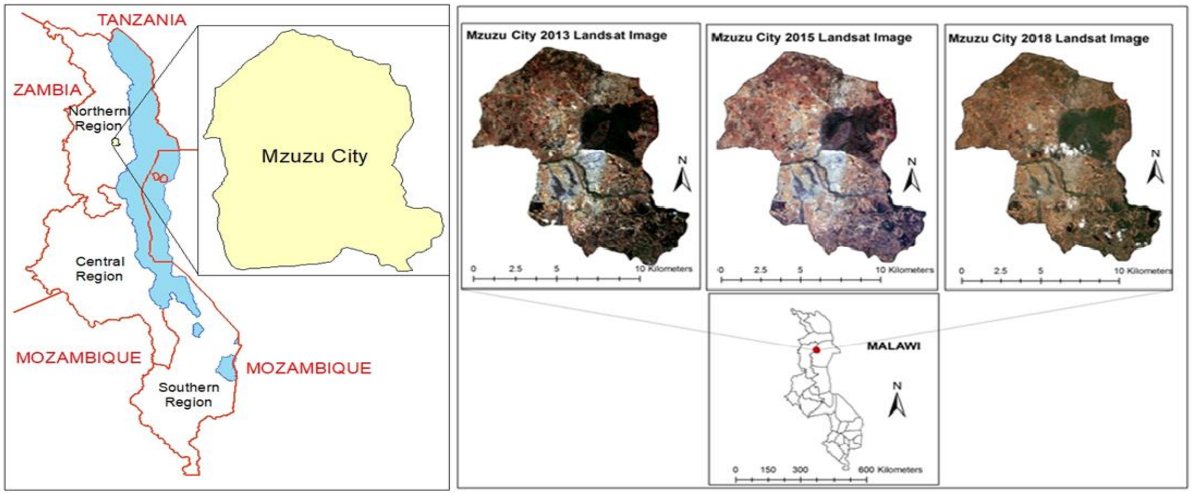

Figure 1: Map showing Mzuzu City and Multi-temporal Landsat 8 Images

2.2. Sources of data

Table 1 contains the data and material used for the study and their respective sources.

Table 1 Data, Data Type and Data sources

	Data/Materials	Data Type	Source
1.	Mzuzu City boundary, drainage system, road network, soil.	Shapefiles	Surveys department, Ministry of Lands, Malawi
2.	Ground Truth and Accuracy Assessment Points	Point data	Global Positioning System (GPS) in Field survey
3.	Mzuzu City Slope and elevation	Raster map	Research generated from DEM
4.	Mzuzu City Landuse/landcover	Maps	Research generated from satellite imageries
5.	Landsat 8 Imageries	Satellite image	Online downloads @ http://earthexplorer.usgs.gov/
6.	Digital Elevation Model (DEM)	Raster	Online downloads @ http://earthexplorer.usgs.gov/
7.	ArcGIS 10.2, QGIS 3.2.1 & Google Earth Pro	GIS Software	Online downloads @ https://download.qgis.org, except for ArcGIS 10.2 which was purchased by the Geosciences department of Mzuzu University.

2.3. Parameter inputs for flood vulnerability analysis

Spatial Analyst and 3D Analyst extensions of ArcGIS 10.2 were used to analyze flood vulnerability using MCE. The selected flood variables of drainage density, landuse/landcover, elevation, slope, and soil were weighted using raster calculator.

Drainage density was generated in ArcMap using the *Line density* function of Spatial Analyst Tool. The streams were extracted from the DEM. *Stream buffering* was later done using the *proximity analysis* from the Analysis Tools. *LU/LC* layer was generated from the 2018 Landsat 8 image. Supervised maximum likelihood classification was done using the urban texture classes as adopted from Stewart and Oke (2012). These classes were collapsed into five main classes of Built up Area/Settlement, Dense trees, Light trees/Bush/Shrub, Bare ground/Paved and Dambo land. Calculation of the area coverage of the different classes of the image was done using the kernel density attribute table. Since the resolution of Landsat 8 image is 30m by 30m (NASA, 2019), the area of each pixel is thus 900 m^2. Therefore the area for each class was calculated by multiplying the observed count of all pixels in each class by 900 m^2.

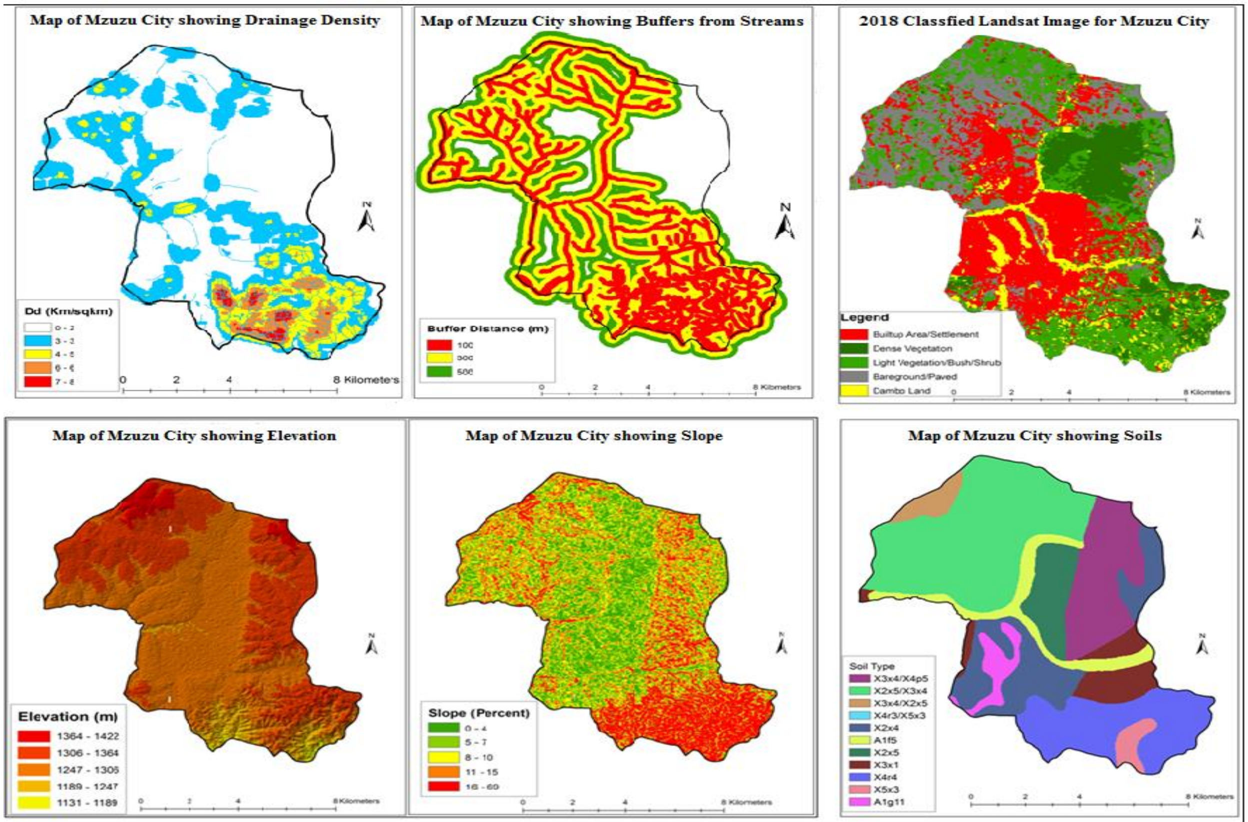

Figure 2: Maps showing Parameter inputs for flood vulnerability analysis

Elevation and *slope* layers were generated from the DEM using the *conversion* tool (i.e. from raster to TIN) of 3D Analyst and the *slope* Spatial Analyst Tool, respectively. Before the actual production of the elevation layer, elevation values for the pixels had to be extracted from the DEM layer via the *build raster attribute table* function from raster properties of Data Management Tools. Slope output layer was given in percentage. The *Soil* layer was obtained from the Surveys department, Ministry of Lands, Malawi.

2.4. Reclassification Process

Reclassification was done using the *inverse ranking method* in the ArcMap platform. The ranking was done for each of the five variables (i.e. drainage density, elevation, slope, landuse/landcover and soil type) in accordance to their degree of influence in flood induction (Njoku et al 2018; Bhadra, Choudhury, & Kar, 2011). A value of 1 was assigned to the class which was deemed to have least influence in flood initiation while class with next level of influence was assigned 2 and 3… in that order. Further, the ranks were grouped into index rating of high and low risk groups (see Table 2).

2.5. Weighting Process

The weighting process was done using the *Weighted Overlay* function of ArcMap's Spatial Analyst Tools. This process combines several raster layers using a common measurement scale and weighs each layer according to its attached significance. The final result of the weighting process is determined by the weight of each variable (Njoku et al 2018; Bhadra, Choudhury, & Kar, 2011). This study considered distance from the river, topography (i.e. elevation and slope), and LU/LC as the most significant variables for flood risk. This is because it was revealed during reconnaissance survey that floods in Mzuzu City typically ensue during rainy season and affect low lying areas covered by settlements. While rainfall has been considered another major variable in certain studies, its influence has been suppressed in this study (*see Table 2*).

The general weighted overlay process in MCA was guided by the equations below.

Scaling Range Formula	=	$\frac{X_i - X_{min}}{X_{max} - X_{min}}$

Overall Score Formula	=	[Criteria score 1 x Weight 1]+[Criteria score 2 x Weight 2]+[Criteria score 3 x Weight 3]+[Criteria score 4 x Weight 4]+...

Source: Maxwell (2018)

Table 2 Multi-criteria evaluation variables

Variables	Class	Reclass (Rates)	Rating Index	Weight (W)
Distance from Rivers (m)	<100	4	High risk	30
	100-300	3	Low risk	
	300-500	2	Low risk	
	>500	1	Low risk	
Elevation (m)	1131-1189	5	High risk	25
	1189-1247	4	High risk	
	1247-1306	3	Low risk	
	1306-1364	2	Low risk	
	1364-1422	1	Low risk	
Slope (%)	0-4	5	High risk	25
	5-7	4	High risk	
	8-10	3	Low risk	
	11-15	2	Low risk	
	16-69	1	Low risk	
Landuse/ Landcover	Built-up Area/Settlement	3	High risk	12
	Light Vegetation/Dambo Land/Shrub/Bareground	2	Low risk	
	Dense Vegetation	1	Low risk	
Soil Types	Eutric Fluvisols	2	High risk	8
	Haplic Lixisols	1	Low risk	

3. Results and Discussion

3.1. Flood risk vulnerability for Mzuzu City

The results of the weighted overlay process show that out of the total 112 sq. km that make up Mzuzu City, the very high flood risk vulnerability areas cover an area of 13.5 sq. km whereas 32.6 sq.km are high risk zones (see Table 3). The areas are in the central part of the city where Chiputula, Chibanja, Mzilawayingwe, Jombo and Mchengautuwa wards are located. These are generally flat dambo areas characterized by low elevation of 1247-1306m above sea level and gentle slopes with slope percentage range of 0–4. These zones fall within the outwash plains of Lunyangwa, Kang'ona and other small streams such as Katoto, Kavuzi and Kajiliwe. They have Eutric Fluvisols soils (*A1f5*) which are very deep and imperfectly drained hence allow very little water to infiltrate (Leenaars, et al 2016). During precipitation, run-off is downslope and water normally accumulates in low lying areas making such areas susceptible to flooding (Salami et. al., 2017).

Table 3 Area Coverage of Flood Risk Zones

Rowid	Label	Pixel Count	Area Coverage (sq. km)	Percentage
1	Very High Risk	15051	13.5	12
2	High Risk	36222	32.6	29
3	Low Risk	51140	46.0	41
4	Very Low Risk	22611	20.0	18
Total		**125024**	**112.1**	**100.0**

The high vulnerability of the central part of the city is further compounded by the tremendous growth the city is currently experiencing in both intensity and extent. Due to this growth, landuse patterns of the City continue changing over time. High population growth has exerted pressure on the available space and has led to the occupation of marginal lands for both settlements and commercial use. Spaces in the outskirts of the City which were meant for agricultural purposes have been turned into settlement areas thereby affecting agricultural productivity. Dambo lands along the streams and steep sloped areas have been encroached by people. During the past five years, Built-up area/Settlement has increased from 25.646 sq. km in 2013 to 32.988 sq. km. in 2015 and to 34.528 sq. km. in 2018. Light vegetation and Dambo areas have been decreasing (see Table 4). Such changes in LU/LC are a call for worry since they increase vulnerability of people to flood risk.

Table 4 Area comparison for the classified Landsat images

		CLASS AREA (sq. km)		
Rowid	**CLASS NAME**	**2013**	**2015**	**2018**
1	Built-up Area/Settlement	25.646	32.998	34.528
2	Dense Vegetation	10.426	6.026	14.58
3	Light Vegetation/Bush/Shrub	41.345	35.344	32.752
4	Bareground/Paved	19.804	25.396	22.964
5	Dambo Land	14.856	12.313	7.253
Total Area		**112.077**	**112.077**	**112.077**

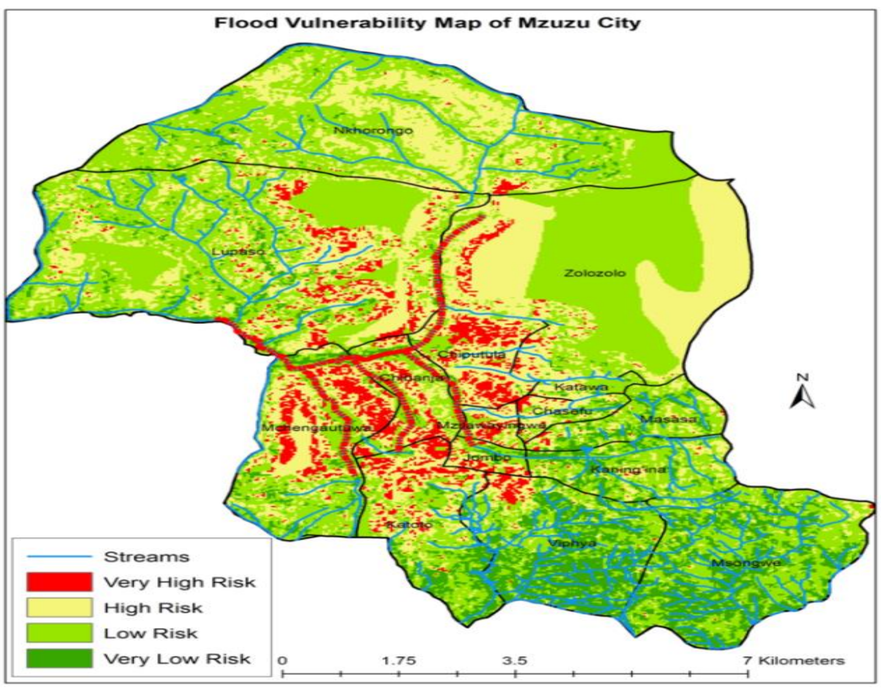

Figure 8: Flood Risk Vulnerability Map of Mzuzu City

Low risk zones are located to the northern and eastern part of the city where Lupaso, Nkhorongo and Zolozolo wards are found. Very low risk areas are in the southern part of the city where Kaning'ina, Masasa, Msongwe and Viphya wards are located. These zones cover an area of 46 sq. km. and 20 sq. km., respectively.

The terrain in this part of the city is rugged and is characterized by high elevation ranging from 1131-1189m above sea level, steep slopes with slope percentage of 16–69 and high drainage density of 7-8km/sqkm. These physical characteristics make the area less vulnerable to flood occurrences as they do not allow water to accumulate and cause flood. However, with the proliferation of informal settlements in these marginal zones, these areas are potential hazardous zones for landslides, mud flows and rock falls (Orok, 2011).

4. Conclusion

Flood vulnerability assessment is an important exercise for decision makers for planning and management purposes. While it is not possible to prevent floods from taking place, flood simulations and risk assessment using MCA analysis in GIS environment are pragmatic tools to reducing flood risk and its impact. This paper presents work carried out in Mzuzu City. The generated composite map in Figure 8 is the resulting map of the assessment. It provides a platform for the quick assessment of potentially hazardous areas and the impact of flood hazard and can guide in the commencement of appropriate measures to reduce its impacts.

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